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Past, present and future experimental tests of quantum nonlocality are discussed. Consequences of assuming that the state-vector collapse is a real physical phenomenon in space-time are developed. These lead to experiments feasible with today's technology.

## I. INTRODUCTION

Central to quantum mechanics is the superposition principle: if  $\psi_1$  and  $\psi_2$  are two mathematical objects representing two possible physical states of a quantum system, then any linear combination, in particular  $\psi_1 + \psi_2$ , represents also a possible state of this system. Accordingly, the  $\psi$ 's are usually called state-vectors. This mathematical formulation of the superposition principle encompasses essentially all peculiar aspects of quantum physics. The wave-particle dualism, for example, is reflected by the fact that the linear addition of waves has a straightforward meaning, but in quantum mechanics it applies even to systems that have well localized effects, like particles. If this would be all the story, then a pilot-wave picture à la De Broglie-Bohm would be most natural: the particle is guided by a wave, like a cork guided by water waves. For example, this model provides a classical picture of the famous two-slit experiment. But the particle-wave dualism is not the entire story of the superposition principle.

In this contribution, we discuss some past, present and future tests of quantum physics. We insist mainly on two points. The first one concerns the importance of quantum nonlocality. Indeed, it is only when the superposition principle is applied to systems composed of a few particles that the most stringent characteristics of quantum mechanics can be tested: if the system is not composed, then a classical picture suffice, as briefly mentioned above; if, on the contrary, the system is composed of many particles, then the complexity of the situation makes it useless for experimental tests, as discussed in the next section. The second point we like to emphasize is the much discussed *collapse of the state vector*. Whether this collapse is a real physical phenomenon or not is a long debate. We approach this delicate question by concentrating on assumptions formulated in such a way that they can be tested with today's technology. Our guide is the tension between quantum nonlocality and relativity: if the collapse is a real physical phenomenon, then it is incompatibility with special relativity and must thus lead to new measurable effects.

In the next section, the measurement problem and EPR-Bell tests are briefly commented, with emphasize on the detection and the locality loopholes (paragraphs IIA and IIB, respectively). In section III four different assumptions about the collapse of the state-vector as a physical phenomenon in space-time are presented and some experimental results reviewed. Finally, a further assumption is discussed in section IV.

## II. A BRIEF HISTORICAL PERSPECTIVE

Einstein, Podolsky and Rosen [1], and Schrödinger [2] showed that when the superposition principle is applied to multiparticle systems, situations even more bizarre (i.e. counter to our classical intuition) than the two-slit experiment occur. A first example is the infamous quantum measurement problem: the superposition principle predicts that if result 1 is possible with the system+measurement apparatus final state represented by  $\psi_1$  and result 2 is possible with final state  $\psi_2$ , then, in principle,  $\psi_1 + \psi_2$  represents also a possible state, although this is never observed. This measurement problem suffers from a serious limitation: while quantum theory admits  $\psi_1 + \psi_2$  as a state, it predicts that the situation represented by  $\psi_1 + \psi_2$  is in practice unobservable. This is due to the unavoidable interaction with the environment which hides the correlations predicted by  $\psi_1 + \psi_2$ . This "hiding" is called decoherence. Whether one finds this solution satisfactory or not is "human dependent"! Some are fascinated by the consistency of the quantum formalism. Some find it strange that the fact that a peculiar prediction can't be tested is counted in favor of the theory: isn't physics about testing the most peculiar predictions of our best theories? Anyway, the fact remains that the measurement problem can't be solved by experiments, at least not with today's technology. But this is still not the end of the story.

Let's apply the superposition principle to a system composed of two spatially separated objects A and B. If object A is in state  $\alpha_1$  and object B in state  $\beta_1$ , then the combined system is in state  $\alpha_1 \otimes \beta_1$ . Consequently,

$$\alpha_1 \otimes \beta_1 + \alpha_2 \otimes \beta_2 \tag{1}$$

must also represent a possible state of the composed system. Moreover, contrary to the measurement problem, states of the form (1) can be produced in controlled environments and can be measured almost perfectly (we shall come back to the "almost" in the next section). States

of the form (1) which can't be written as a product (by changing the basis) are called entangled [3,4]. Entangled states have bizarre properties. First they allow remote state preparation: by performing a measurement on the object A, object B is prepared in a well defined state. Note that one can't decide the state in which to prepare B, but once the measurement result on A is registered, the state of B is well determined. This bizarre prediction can be tested: perform independent measurements on many identically prepared objects and register the results. Then, select the cases where object B was prepared in a specific state and check that the measurement outcomes on B for these cases are compatible with the predicted state. But this is still not the entire story.

Bell has showed that the situation is even more bizarre [5]. Let  $a$  and  $a'$  denote possible measurements on A with results  $\alpha$  and  $\alpha'$ , respectively, and similarly  $b$  and  $b'$  measurements on B with results  $\beta$  and  $\beta'$ . Then  $(\alpha, \beta)$  and  $(\alpha, \beta')$  denote possible joint results when  $a$  is measured simultaneously with  $b$  and  $b'$ , respectively. Now, it seems almost obvious that if the objects A and B are spatially separated, then results on A do not depend on what is measured on B. This locality assumption implies that if result  $\alpha$  is registered, this does not depend on which measurement  $b$  or  $b'$  was performed on B, and vice-versa. Hence, ascribing to the results the values  $\pm 1$ , they satisfy the following inequality:

$$\alpha \cdot \beta + \alpha \cdot \beta' + \alpha' \cdot \beta - \alpha' \cdot \beta' = \quad (2)$$

$$\alpha \cdot (\beta + \beta') + \alpha' \cdot (\beta - \beta') \leq 2 \quad (3)$$

Consequently, the locality assumption implies that the expectation values  $E(a, b) \equiv \text{Mean}\{\alpha \cdot \beta\}$  satisfy the CHSH-Bell inequality [6]:

$$E(a, b) + E(a, b') + E(a', b) - E(a', b') \leq 2 \quad (4)$$

But, according to quantum mechanics, this is not so! All entangled pure states violate the inequality (4) for some properly chosen measurements [7].

Consequently, quantum theory is nonlocal. But is that serious? Should we bother? It is instructive to recall that the Einstein-Bohr debate was considered during tens of years as mere philosophy. Then, came John Bell and his inequality who turned the question into experimental physics<sup>1</sup>. More recently, A. Ekert [8] and Ch. Bennett, G. Brassard and D. Mermin [9] demonstrated that quantum correlation can be used for secure communication, hence the question became part of applied physics! No doubts: quantum nonlocality is central both for our understanding of the most precise theory ever produced and

for the huge potential applications of quantum technologies, for example in the field of quantum communication and information processing [3,4].

When Bell discovered his inequality, a first surprise was that no existing experimental data could be used to test the inequality. Hence, new experiments had to be designed and carried out. The first experiments gave conflicting results, a fact which probably explains in part why Clauser's experiment is too often forgotten [10]. Since Aspect and co-workers experiments in the early 80's [11] many laboratories around the world performed experiments confirming the bizarre predictions of quantum mechanics (see [12,13] and references therein). A few years ago, we demonstrated that the experiment can also be brought out of the lab [13,14]. Using standard telecom fibers, we could violate Bell inequalities by photons that propagated 8 and 9 km, respectively, and were analysed in two Swisscom stations distant by more than 10 km. This demonstrated the robustness of entanglement and its potential for applications in quantum communication.

But the story does not end with all these beautiful experiments! Indeed, first these experiments use real, i.e. non-ideal devices, hence suffer from some loopholes. Next, once one admits the existence of quantum nonlocality, new questions arise. The next two paragraphs, IIA and IIB, briefly summarise the detection and the locality loopholes. Then, the sections III and IV present ideas for new tests and some first results.

## A. The detection loophole

Real detectors have a finite efficiency. Actually, almost all experiments to date used detectors with efficiencies below 50%, this mean that the detectors miss most of the particles and that the correlations are measured on less than a quarter of the particle pairs. From the standard quantum mechanics point of view, this is easy to explain and does not cause any problem. However, if one admits that additional variables, not yet discovered, could exist, then this is a serious problem [15]. For example suppose that we did not know that photons have a variable called polarization. Polarizer and polarization sensitive detectors would nevertheless exist! Hence, from the local variable point of view it is very plausible that the detectors and other elements we use in our experiments are sensitive to these additional variables, even if we are not (yet) able to master them. It is not difficult at all to device models explaining all existing results using only local variables and the assumption that the detectors are sensitive to these local variables (see e.g. [16]).

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<sup>1</sup>Actually, Bell's original inequality [5] is untestable because it assumes perfect correlations. It is the merit of Clauser, Horn, Shimony and Holt [6] to have derived the inequality (4) well suited for experimental investigations.

In most tests of Bell inequality, the settings  $a$  and  $b$  are changed very slowly. Often one even keeps them fixed until enough data are acquired to compute the corresponding correlation  $E(a, b)$ . Consequently, one could imagine that the analysers somehow influence the source and that the photon pairs are emitted in a state which depends on the analyzers. Although such a solution would require a completely new kind of influence, it would not require any superluminal signaling. Hence it is worth testing. Aspect and co-workers performed the first test closing this loophole, using quasi-periodic acousto-optic modulators [17]. More recently, G. Weihs and co-workers performed an experiment using fast polarization modulators [12]. In this experiment, the settings were chosen by random generators, based on quantum mechanics. W. Tittel and colleagues also performed an experiment which can be considered closing this loophole [14,18]. In the later the random choice was also of quantum origin, but implemented using an internal degree of freedom of the tested photons, independent from the variable used to test the inequality.

As shown in ref. [18], these tests of the locality loophole are not independent of the detection loophole. The story on the loopholes in Bell tests is thus not yet completely closed, although a result contradicting quantum mechanics in these nowadays standard experiments would come as a huge surprise.

### III. "SPEED" OF THE "SPOOKY ACTION AT A DISTANCE"

Let's assume that the collapse of the wavepacket is a real physical phenomenon. Some physicists will immediately react that such an assumption is not necessary. At this point one could start to argue. The argument would probably turn around some form of the measurement problem, or involve a many-world interpretation [19]. But none of these can be tested with today's technology. Consequently, better than arguing, let's explore the consequences of the assumption! Indeed, wouldn't it be nicer to argue against the concept of collapse as a physical phenomena by designing and performing experiments, rather than arguing that collapses might not be required to explain present day data?

If there is a physical phenomenon in space-time, there must be a speed. What is the speed of the "collapse" and how could one measure it? First about semantics. We don't have in mind the time it takes for a collapse process to take place. Rather we think of the time it takes before distance systems entangled with the measured one collapse themselves. Hence, we believe that "speed of

quantum information" is an appropriate name<sup>2</sup>. Other possibilities would be "speed of quantum influence", or "speed of the spooky action", but we consider them as inappropriate to design an assumed real phenomenon. So, let's call this hypothetical speed, "speed of quantum information" and denote it  $v_{QI}$ . As any speed,  $v_{QI} < \infty$  and its value depends on the reference frame. Accepting the results of Bell tests, we know that this speed must be superluminal,  $v_{QI} > c$ . Hence, even the chronology depends on the reference frame. Assuming that there is a cause – a probabilistic cause in the form of a measurement outcome here – and an effect there, related either deterministically or probabilistically, the reference frame (if it exists) must be determined either by the very condition of the experiment itself, or by cosmology. In this section, we review four possibilities. The three first ones have been tested experimentally (though sometimes with additional assumptions). In the next section IV we elaborate on some possibly future directions.

#### A. Laboratory frame

A first very natural assumption is that the reference frame is determined by the massive local environment of the experiment, i.e. by the laboratory frame, or, in case of our long distance Bell experiment, by the Geneva frame. Indeed, as long as all the parts of the experiment are at rest in the lab reference frame, it is a natural assumption (in paragraph III C we consider what could happen if the different parts are in relative motion). A testable consequence of this idea is that if the two measurements on the two entangled particles take place simultaneously in the lab frame, then, however large  $v_{QI}$  might be, each particle produces a result before being informed that the other particle also undergoes a measurement. Consequently, in case of perfect simultaneity in the lab frame, the quantum correlation should disappear. In real tests the measurements are never perfectly simultaneous. But a finite precision in the timing, sets a lower bound to the speed of quantum information. In 1999 we performed an experiment in which careful fiber length and chromatic dispersion adjustments provided a timing accuracy of  $\pm 5$  ps over a distance of 10.6 km, setting the lower bound [20,21]:

$$v_{QI} \geq \frac{2}{3} 10^7 c \quad (5)$$

where  $c$  denotes the speed of light. This is a large number indeed! It is tempting to conclude that the laboratory

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<sup>2</sup>Admittedly, there is the danger that one (intentionally or not!) forgets the qualification "quantum" and concludes that information propagates faster than light. There will always be ways to mistreat terminology.

(Geneva) frame is not the correct one. But one should be careful. For centuries, the fastest measured speed was that of sound and the speed of light was considered ill defined or infinite. However, first measurements of the speed of light found values 6 orders of magnitude larger than the speed of sound in air<sup>3</sup>.

## B. Cosmic background radiation frame

The most natural singled out reference frame in cosmology is determined by the cosmic background radiation. In a recent paper we analyzed our 1999 experiment in this context [22]. The result is that our data set a lower bound of

$$v_{QI} \geq 2 \cdot 10^4 c, \quad (6)$$

again an impressive value. Improved experiments, in particular with faster data acquisition, could still increase this bound by several orders of magnitude (or find new physics!).

## C. Detector frame

A third quite natural assumption is that the reference frame is determined by the massive device that triggers the collapse. This possibility is inspired by, though different from Antoine Suarez ideas [23,24]. It is similar to the laboratory frame assumption discussed in subsection III A. The most important difference is that different *trigger devices* can be in relative motion and thus determine different frames. In particular one can think of situations where two *trigger devices* both trigger a collapse before the other, each in its own inertial reference frame! In such a case the concept of collapse as a causal explanation collapses!

Testing this assumption is difficult, but not impossible. Using the 5 ps timing accuracy over 10 km obtained in our 1999 experiment, a relative speed of 50 m/s between the two trigger devices suffices [20,21]. More delicate is the question "what is a trigger device"? i.e. what triggers the collapse? Again many physicists will answer: "nothing, since collapses do not exist!". But we prefer to make testable assumptions. Probably, the assumption that detectors are trigger devices would be generally considered as natural. But this makes the experiment specially difficult: one would have to set the detectors, in our case liquid nitrogen cooled Ge avalanche photodiodes, in motion with large velocities. This practical

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<sup>3</sup>Clearly, this is only an analogy. Contrary to quantum information, both sound and light carry energy and classical information.

difficulty does of course in no way reduce the interest of assuming that the detectors are the trigger devices and we do hope to see an experiment along this line in the future. However, another interesting assumption is that any irreversible absorption acts as a trigger device<sup>4</sup>. But then, how could one register the results? In [13,14] we argue that this is still possible if one output port of the analyzer is connected to an absorbing material and the other output port to a real detector; the only requirement being that the absorption takes place well before the particle sees the detector, as in fig. 1 where the absorber A is much closer to the interferometric analyzer than the detector APD3. In this way, the particle emerges from the analyzer from both output ports, in superposition with probability amplitudes as in standard quantum mechanics. The particle then first encounters the absorber which triggers a collapse. Either the particle is absorbed and the collapse reduces the probability amplitude of the detector path down to zero, or the particle is not absorbed and the collapse raises the probability amplitude of the detector path up to one. This is just standard quantum mechanics. Note that in this configuration the detectors do not trigger any choice, they only reveal the results of the measurements actually performed by the absorbers. In practice, because of the detectors inefficiencies most results are never registered. We thus need to assume that the set of collected data constitute a fair sample of all events. This is an assumption independent from the hypothesis that massive absorber determine the reference frames in which the collapse take place, but it is not a new assumption: as discussed in section II A all Bell tests to date must use the fair sampling assumption.

Let us emphasize another aspect of this experiment. It is known since the very early days of relativity that the time ordering of events may depend on the reference frame. In our experiment, two correlated events are made to happen in such a way that each event in its own natural reference frame happens first. Moreover, this relativistic effect could be realized using an "almost every day" speed, 100 m/s, the speed of a Ferrari! This is of interest, even independently of the quantum collapse issue.

The experimental details are given in [20,21]. The main conclusion is that the quantum correlation are observed, even in this *before-before* configuration. This result contradicts the assumption that absorbers determine the reference frame in which the collapse propagates.

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<sup>4</sup>In [20,21] we argued that if detectors are assumed to be trigger devices, then absorbers would equivalently act as trigger devices. Indeed, the essential physics of detectors is the irreversible absorption which takes place in the first microns of the upper semi-conductor layers. We still believe that this is a valid reasoning, but prefer here to present the absorber case as an independent assumption, in order to avoid confusion between different kinds of arguments.

A further interesting hypothesis assumes that the preferred frame is determined by the massive device where the particle chooses its path, i.e. the *choice device*<sup>5</sup>. This idea is inspired by the pilot-wave picture à la De Broglie-Bohm and has been first proposed by Suarez and Scarani [23], and developed in [24]. In this picture, the quantum state vector is called a wave and is assumed to guide a point particle. Hence, in this model, the particle's position is a variable in addition to the usual quantum state vector (note that the position variable is not hidden, quite on the contrary it is the only variable we access directly. In this model, it is the state vector which is hidden!). Beam splitters and polarization analyzer are examples of devices where the particle's position makes a choice, i.e. they are examples of *choice devices*. It might be interesting to speculate on how physics would have developed, in particular how the Einstein-Bohm controversy would have evolved, had De Broglie discovered earlier the model that Bohm published in the 1950's. But, even more interesting is that in this model it is very natural to assume that the reference frames defined by the *choice devices* determined the chronology. Accordingly, when two entangled photons encounter two beam splitters in relative motion such that each photon is "analyzed" by its beam splitter before the other photon, then, again, a before-before configuration happens and the quantum correlation should vanish. This is a very natural extension of the pilot wave model. And it is a testable one. We are working on realizing such an experiment, using traveling acoustic waves as moving beam splitters [25].

#### IV. ONE STATE-VECTOR PER REFERENCE FRAME?

So far we have always assumed that there is a unique "state of the universe". Many theorists have argued that a way out of the conflict between relativity and collapses as real physical phenomena is to assume that the state vector itself depends on the reference frame. Hence, each foliation of space-time has its own  $\psi$ . The different state vectors are related such that they predict the same statistics of measurement outcomes. Along this way, some relativistic models of collapses are developed [26]. This raises however the question of the uniqueness of data [27]. This problem also exists in classical mechanics, though there it reduces to the uniqueness of initial conditions.

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<sup>5</sup>In [20,21] we used the terminology of *choice device* also for detectors and absorbers, i.e. for what we call here *trigger device*.

In quantum mechanics the problem is more delicate, because real choices happen all the time. With a unique state vector and real collapses, unique data arise naturally in Newtonian relativity with an absolute time. But the real problem is the compatibility between the uniqueness of quantum data and Einstein relativity, where timing is relative.

Associating one state vector to each reference frame does not solve the uniqueness of data problem. But again it is instructive to look at long distance quantum correlation with moving devices and to formulate testable hypothesis. In figure 1 with the moving absorber (the wheel) there are, in the context under consideration, two state vectors. The first one,  $\psi_1$ , is associated to the moving absorber, the other one,  $\psi_2$ , is associated to all the other devices, in particular to the detectors. Hence, all measurement results to date are compatible with the idea that the detectors see only  $\psi_2$ , and not  $\psi_1$ , while the absorber only trigger the collapse of  $\psi_1$  without affecting  $\psi_2$ . To test this, one should replace the moving absorber by a real detector. The assumption is that the data from this moving detector show no correlation with the data from the distant entangled particle, but the data from detectors at rest shows the quantum correlation. A surprising prediction of this assumption is that in some cases both the moving and the static detectors detect the particle! and sometimes none detects it (even assuming perfect detectors). On the mean, the number of counts of each detector corresponds to the standard predictions, but not in individual cases. There would be a serious question of energy conservation. But is this really new? Already in the old EPR paradox, the momentum correlation corresponds to kinetic energy correlation: the kinetic energy measured on one particle determines the energy of the other particle. Hence, the distant particle (i.e. not in direct contact with the measurement apparatus) can end in states with different energies. Where does this energy come from or go to?

#### V. CONCLUSION

The story of quantum nonlocality is fascinating. We could take advantage of this to promote Physics! We already learned a lot from it, in particular about the weirdness and importance of entanglement in the quantum world. We are also learning how important entanglement can be for our technology, namely that we could exploit entanglement to perform tasks classically impossible, like quantum cryptography and many others. This field is nowadays well recognized under the general name of quantum information processing [3,4]. But the story is not at the end. Using new technologies, revolutionary assumptions can be tested. Admittedly, some of the assumptions discussed in this contribution are wild. But they are testable with today's technology and they provide great intellectual excitement. Moreover, they are

very natural in the context of the debate about the existence or non-existence of state-vector collapses, a question which triggered animated discussions and disputes since the very early times of quantum mechanics, 100 years ago. It is worth realizing that there are not that many alternatives to the existence of "real collapses": without collapses the logical implication of the superposition principle is that all possibilities co-exist, in the form of some multiverse [19]. But this huge superposition can't be tested directly. Isn't it nice to argue in favor or against the concept of collapse as a physical phenomena by designing and performing experiments of the kind discussed in this contribution!

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## FIGURE CAPTION

Schematic of the experiments discussed in sections III A, III B and III C. It consists of a photon pair source entangled in energy-time and two interferometric analyzers separated by 10.6 km, see [14]. In the first experiments, the avalanched photodiodes APD1 and APD2 are set at exactly the same distance from the source, so that in the Geneva reference frame they register counts simultaneously with a timing accuracy of  $\pm 5$  ps. In a second experiment, the detectors APD1 and APD2 are replaced by two absorbing surfaces. The absorber A is static and the second absorber is moving at 100 m/s on a rotating wheel. They are adjusted such as to be at the same distance from to source within  $\pm 1$  mm. With this precision, each absorber encounters a member of the photon pairs before the other, each in its own (quasi) inertial reference frame. The detectors APD3 and APD4 are connected with longer fibers such that each photon meets first the absorber, next the detector. For further information about the experiment, see [21].